

ADVANCED BIOMASS REBURNING

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ABSTRACT

While biomass cofiring has been successfully demonstrated in several coal-fired utility boilers, a value-added option is to utilize biomass above the main burner as a reburning fuel. Biomass which may include wastewood, straw, agricultural waste, etc. is inexpensive and have a potential for lower cost NO_x reduction with comparable performance to that of gas and coal reburning. This new concept presents a means for utilizing both energy content of biomass and its chemical constituents (nitrogen- and alkali-containing compounds) which can promote the chemical reactions of NO removal from combustion flue gas. The United States Departments of Energy and Agriculture are currently funding an R&D program with overall objective to move the biomass reburning technology to the full-scale demonstration level. This paper presents results of combustion experiments and modeling studies during the second year of the R&D program. Fuels under investigation include natural gas, furniture waste, willow wood and walnut shells. Performances of different biomass fuels have been examined in a 300 kW (1×10⁶ Btu/hr) Boiler Simulator Facility at different experimental conditions. Tests showed that biomass is as an effective reburning fuel as natural gas.

INTRODUCTION

An environmental problem faced by the power generation industry involves controlling flue gas emissions from coal fired boilers. Reburning is a commercial two-stage fuel injection technology which is currently most promising for low-cost NO_x control. In this firing method, the main fuel is coal or oil (80-90% of the total) and the remaining fuel (reburning fuel) might be natural gas or other combustibles. Basic natural gas reburning can achieve 60-65% NO_x control.

While biomass cofiring has been successfully demonstrated in several coal-fired utility boilers, a value-added option is to utilize biomass above the main burner as a reburning fuel. Biomass which may include wastewood, straw, agricultural waste, etc. is inexpensive and have a potential for lower cost NO_x reduction with comparable performance to that of gas and coal reburning.

EER currently is working on development and commercialization of a new technology of advanced reburning (Zamansky et al., 1996 and 1997). Advanced reburning is being developed for natural gas and is a combination of basic reburning and N-agent/promoter injection. The promoters are alkali additives that enhance NO_x reduction. Utilization of biomass in advanced reburning has potential to achieve about 90% NO_x control in coal fired boilers and promises certain advantages over other fuels. This new concept presents a means for utilizing both energy content of biomass and its chemical constituents (nitrogen- and alkali-containing compounds) which can promote the chemical reactions of NO removal from combustion flue gas.

The United States Departments of Energy and Agriculture are currently funding an R&D program with the overall objective to move the biomass reburning technology to the full-scale demonstration level. Specific objectives of the program include: (1) optimization of biomass reburning in pilot-scale tests; (2) development of engineering modeling tools for commercial applications of biomass reburning; (3) evaluation of potential boiler impacts, such as slugging and fouling; and (4) evaluation of biomass fuel processing/handling economics as part of an overall economics and performance analysis for biomass reburning.

Total R&D program includes both DOE FETC and Phase II SBIR USDA projects. Both projects are conducted in close coordination with each other. The DOE FETC project is performed jointly by EER team, FETC R&D personnel, Antares, and Niagara Mohawk Power Corporation (NMPC). The project involves modeling activities (chemical kinetic, computational fluid dynamics, and physical modeling), economic studies of biomass handling, and experimental evaluation of slagging and fouling. The USDA Phase II SBIR projects includes pilot-scale process optimization and design activities.

If the results are successful, NMPC plans to demonstrate the biomass reburning technology at full scale. Some of the tested fuels will be utilized in large-scale EE Biomass Power sponsored Biomass Power For Rural Economic Development projects (Niagara Mohawk-Salix and Chairton Valley).

This paper presents results of modeling studies and pilot-scale combustion experiments on performance of furniture waste, willow wood, and walnut shells as reburning fuels in comparison with natural gas.

EXPERIMENTAL SETUP

The pilot scale tests were conducted in EER's 300 kW (1×10^6 Btu/hr) Boiler Simulator Facility (BSF) described earlier (Ho et al., 1993). The BSF is designed to provide an accurate subscale simulation of the flue gas temperatures and composition found in a full scale boiler. It consists of a burner, vertically down-fired radiant furnace, and horizontal convective pass. A variable swirl diffusion burner with an axial fuel injector is used to simulate the approximate temperature and gas composition of a commercial burner in a full scale boiler. Primary air is injected axially, while the secondary air stream is injected radially through the swirl vanes to provide controlled fuel/air mixing. Numerous ports located along the axis of the facility allow supplementary equipment such as reburn injectors, additive injectors, overfire air injectors, and sampling probes to be placed in the furnace.

The cylindrical furnace section is constructed of eight modular refractory-lined sections with an inside diameter of 0.56 m (22 in). The convective pass is also refractory lined, and contains air cooled tube bundles to simulate the superheater and reheater sections of a full scale utility boiler. Heat extraction in the radiant furnace and convective pass is controlled such that the residence time-temperature profile matched that of a typical full scale boiler. A suction pyrometer is used to measure furnace temperatures. The temperature gradient in the range 1200-1700 K (1650-2600 °F) is about -300 K/s (-540 °F/s).

A series of pilot scale tests was conducted in the BSF to characterize biomass reburn performance as a function of key process variables. The reburn fuels of primary interest were a pelletized furniture waste and willow wood. For comparison, several tests were also conducted with natural gas and walnut shells. Natural gas and Illinois and Ohio coals were used as primary fuels.

All solid fuels were pulverized for the tests. The coals were pulverized in a bowl mill such that 70% passed through a 200 mesh sieve. The furniture waste and walnut shells were pulverized in a hammer mill. Size distribution was varied by installing different screens in the hammer mill and by running samples through the mill multiple times. For the furniture waste four grinds were tested: 9%, 21%, 27%, and 48% through 200 mesh. The 48% < 200 mesh grind was used for most of the tests. The walnut shells were more brittle than the furniture waste pellets and provided a finer size distribution. For the walnut shells a single grind of 55% < 200 mesh was tested.

It was found that the willow wood was fibrous and considerably more difficult to process than other biomass samples. It was received as branches up to 0.6 m (2 ft) long. It was pre-processed by running through an industrial wood chipper and then pulverized in a hammer mill. The willow wood was difficult to convey through the hammer mill and provided larger size particles than those obtained with other biomass samples. For example, passing the willow wood through the hammer mill with a 0.015 m (1/16 in) screen gave a size fraction of 23% less than 200 mesh, whereas under the same conditions the furniture waste size was 40% less than 200 mesh. The baseline size fraction for the willow wood reburn tests was 23% less than 200 mesh.

EXPERIMENTAL RESULTS ON BIOMASS REBURNING

Figure 1 shows reburn performance for willow wood, furniture waste, walnut shells and natural gas as a function of reburn heat input for Illinois coal as primary fuel.

NO reduction provided by the furniture waste was better than natural gas at 10% reburning. For furniture waste reburning, maximum NO reduction was 58%, achieved at 15% reburn heat input. The walnut shells provided a maximum of 65% NO reduction at 20% reburning. Willow wood reburning gave a maximum of 51% NO reduction at 20% reburning. Walnut shell reburn performance was slightly better than that of natural gas at lower reburn heat inputs, and worse than natural gas at higher reburn heat inputs. Performance of willow wood was worse than natural gas at all reburn heat inputs. Difference in the performance of biomass fuels are due to their different compositions: walnut shells have high volatiles, low nitrogen, and very high potassium content. The willow wood has high volatiles and low ash. The ash from the willow wood has low sodium and notably high P_2O_5 .

EER's previous reburn test work has shown that the main fuel type can have an impact on reburn performance. It is believed that main fuel parameters of importance include concentrations of sodium, potassium, chlorine, and sulfur. Figure 2 compares results for furniture waste and willow wood reburning obtained with Illinois coal, Ohio coal, and natural gas as main fuels. NO reductions were very similar for the two main coals for both biomass fuels, with natural gas slightly better than both coals.

The degree to which biomass is pulverized involves trade-offs between improved reburn performance and increased fuel processing cost. To provide data to assist with making such value judgments, reburn tests were performed at different particle size distribution.

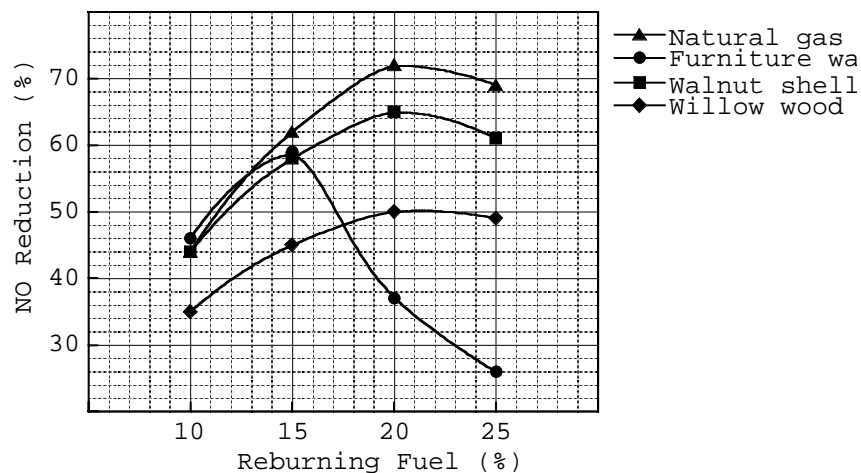


Figure 1. Reburning Performance of Different Fuels. Main Fuel: Illinois Coal. Reburning Fuel Is Injected at 1700 K (2600 °F), $[NO]_i = 416$ ppm. OFA Is Injected at 1450 K (2100 °F). Furniture Waste Size: 48% < 200 Mesh, Walnut Shells Size: 55% < 200 Mesh, Willow Wood Size 23% < 200 Mesh.

Four furniture waste grinds were tested: 9%, 21%, 27%, and 48% through 200 mesh. As shown in Figure 3, performance improved with decreasing biomass particle size. At 10% reburning, NO reduction increased from 42% at 9% < 200 mesh to 67% at 48% < 200 mesh. The finer grinds also exhibited some advantages with respect to carbon burnout, as discussed later. However as shown in Figure 3, with willow wood reburning particle size had minimal effect on reburn performance. At 15% and 20% reburning NO reduction decreased slightly with decreasing particle size, whereas at 10% reburning NO reduction stayed the same. It is possible that due to the extremely high volatiles content of the willow wood (82.29%, dry basis), the fuel is so highly reactive that finer grinding provides limited benefits. Since finer grinding corresponds to significantly greater processing cost, it is advantageous for willow wood to provide high performance with large particles.

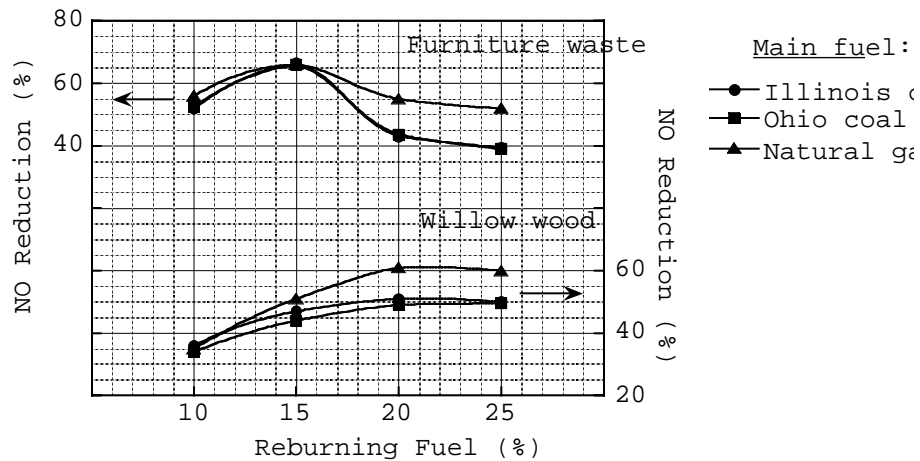


Figure 2. Comparison of Furniture Waste and Willow Wood Reburning with Different Primary Fuels.

Initial NO concentration (NO_i) was varied from 400 to 900 ppm with furniture waste and from 400 to 800 ppm with willow wood as reburn fuels and Illinois coal as the main fuel. For the most part furniture waste performance was fairly flat at NO_i decreased from 900 to 600 ppm, and then began to fall off as NO_i further decreased to 400 ppm. The furniture waste performed better than natural gas at 10% reburning, although natural gas was better at 15% reburning. For willow wood NO reduction increased by 10 to 12 percentage points as NO_i increased from 400 to 800 ppm. Willow wood reburn performance was significantly worse than natural gas reburn performance.

Reburn performance generally improves with decreasing overfire air (OFA) injection temperature, i.e. with increasing reburn zone residence time. OFA temperature was varied from 1530 K (2245 °F) to 1370 K (1960 °F). It was observed that NO reduction decreased with increasing OFA temperature.

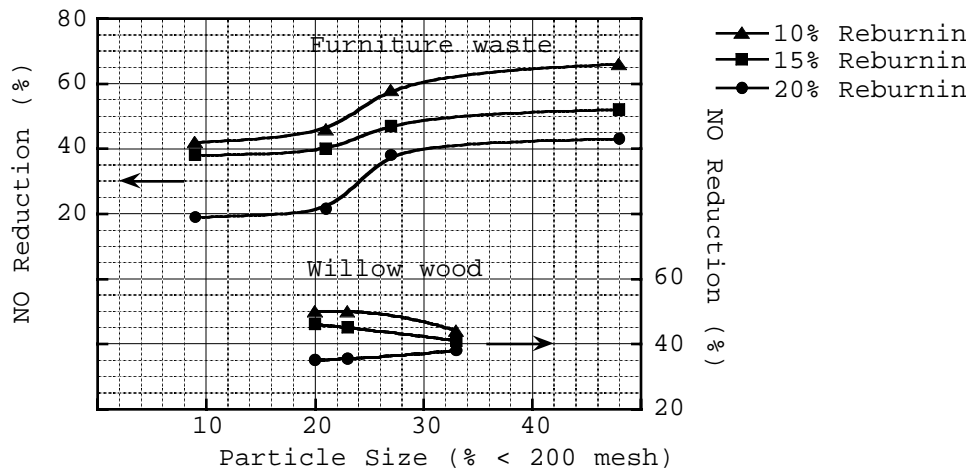


Figure 3. Furniture Waste and Willow Wood Reburn Performance as a Function of Particle Size.

Fly ash carbon content is important both from the standpoint of recovering fuel energy content and finding a market for the fly ash. Test conditions in fly ash tests included baseline coal firing, natural gas reburning, furniture waste reburning at three particle size

distributions, and walnut shells reburning. For all tests Illinois coal was the main fuel. Results are summarized in Table I.

Carbon in ash was slightly higher for biomass reburning than for baseline coal firing. However, carbon in ash decreased with finer reburn fuel size distributions. Carbon in ash for biomass reburning was slightly better than that for natural gas reburning, and in all cases carbon concentrations were well below 1%.

Table I. Carbon in Ash Tests.

Reburn fuel	%<200 mesh	Reburn Heat Input (%)	C in Ash (%)
None (baseline)	–	None	0.07
Natural gas	–	20	0.61
Furniture waste	48	20	0.19
Furniture waste	27	20	0.25
Furniture waste	21	20	0.31
Walnut shells	55	20	0.20

KINETIC MODELING OF THE REBURNING PROCESS

The objective of kinetic modeling is to create a model for predicting the NO_x control performance via reburning. The model currently includes homogeneous reactions only.

Since the experimental performance of biomass as a reburning fuel is compared with that of natural gas, the kinetic model was first applied to natural gas reburning. Modeling of specific biomass fuels is currently in progress.

Modeling was done with a kinetic mechanism that combined reactions relevant to reburning from GRI-Mech 2.11 (Bowman et al., 1997) with SNCR reactions from Miller and Glarborg (1996). The total mechanism included 418 reactions of 64 chemical species.

The EER chemical kinetic code ODF, for “One Dimensional Flame” (Kau and Tyson, 1987) was employed. ODF treats a system as a series of plug flow reactors. Each reactor described one of the physical and chemical processes occurring in a boiler: addition of the reburning fuel, NO_x reduction as a result of the reaction with the reburning fuel, addition of OFA, and oxidation of products.

The mixture entering the first reactor corresponded to products of methane combustion in air with stoichiometric ratio $\text{SR}_1 = 1.1$. The reburning fuel (natural gas) was added to the main stream of reactants in the first reactor. The amount of the reburning fuel varied to provide a stoichiometric ratio SR_2 at the beginning of the first reactor from 0.84 to 0.99. The second reactor described the process of NO removal in the reburning zone after the reburning fuel and flue gas are mixed. The third reactor described the process of OFA mixing with flue gas. The amount of OFA added varied such that the total mixture composition (including previously added fuel) at the beginning of the third reactor corresponded to $\text{SR}_3 = 1.15$. The fourth reactor described oxidation of products of incomplete combustion.

Physically, the process in the first reactor can be described as mixing of the reburning fuel with the main stream of gases. Proper modeling of mixing requires a combination of kinetic and gasdynamic equations, a feasible but not simple undertaking for a detailed chemical

mechanism. As a first approximation, the gasdynamic mixing process was simulated by assuming that mixing just retards the rate at which the additive is delivered to the system, so that the initial concentration of the additive in each experiment increased within mixing time from zero to its final value (distributed reagent injection). Calculations were done for mixing times changing from 0 ms (instantaneous mixing) to 150 ms. Estimation of mixing time made using a droplet evaporation model for typical BSF conditions gave a value of about 100 ms. Mixing was modeled in a one dimensional approximation, meaning that one or more reagents were added to the main stream over period of time, and at each moment mixing was assumed to be instantaneous. Temperatures of the main gas stream and injected substances were assumed to be the same.

Calculations showed that the mixing process in the reburning zone significantly affects modeling predictions at all SR_2 , while mixing in the OFA zone has noticeable effect on NO removal only at $SR_2 > 0.95$. Figure 4 shows the influence of mixing time in both zones on NO removal. Introduction of mixing in calculations significantly improves process performance. The significant effect of mixing in the reburning zone can be explained taking into account the fact that the value of mixing time is longer than the characteristic time of the chemical reaction. Since the temperature in the OFA zone is lower and the corresponding time of the chemical reaction is longer, mixing in the OFA zone has only a minor effect on NO removal.

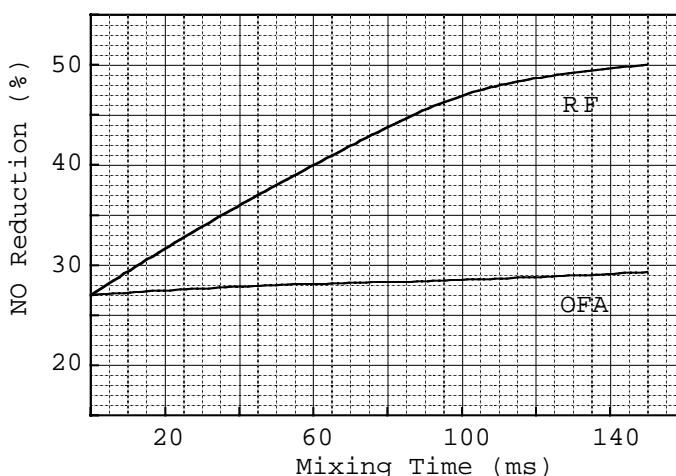


Figure 4. Predicted Effect of Mixing Time in Reburning and OFA Zones on NO Removal. Reburning Fuel Is Injected at 1700 K (2600 °F), OFA at 1422 K (2050 °F). $SR_2 = 0.99$, $[NO]_i = 600$ ppm.

Figure 5 shows comparison of experimental results on basic reburning with modeling predictions. The model gives a close description of the experiments on basic reburning. For SR_2 slightly less than unity the model gives steeper than experimental dependence of NO removal efficiency on the amount of the reburning fuel added. For rich mixture compositions ($SR_2 < 0.86$) the model underpredicts NO removal efficiency. These deviations can be explained by simplification of the mixing process in the current model.

In agreement with experimental data, modeling shows that injection of OFA at lower temperatures is more favorable. However, at lower temperatures the efficiency of CO conversion to CO_2 is reduced. Modeling also shows that the efficiency of NO removal decreases as initial NO concentration decreases.

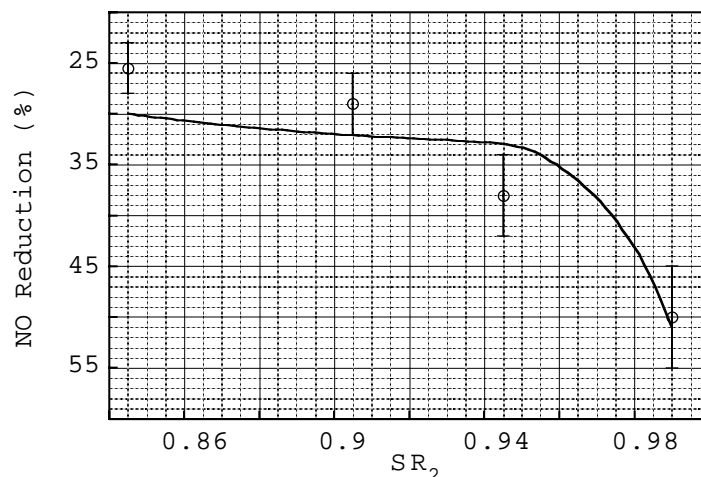


Figure 5. Comparison of Experimental Results on Basic Reburning with Modeling Predictions. Reburning Fuel is Added at 1700 K (2550 °F), OFA at 1422 K (2050 °F). $[NO]_i = 600$ ppm.

The kinetic mechanism developed for natural gas reburning will be used for modeling of biomass reburning. Since the kinetic mechanism extends to only C_1 and C_2 hydrocarbons, the biomass fuel will be represented by a mixture of decomposition products, thus assuming rapid breakdown of the reburning fuel. The fuel oxygen is assumed to form CO in the substoichiometric environment. The remaining hydrocarbon component will be represented by a mixture of C_1 and C_2 hydrocarbons. The composition of decomposition products will correspond to the biomass ultimate analysis.

CONCLUSIONS

1. Furniture waste and walnut shells provided similar NO_x control as that of natural gas in basic reburning at low heat inputs and performed worse at high ones. Performance of willow wood was worse than that of natural gas at all heat inputs.
2. Optimum heat input for furniture waste is about 15%, and for other biomass fuels about 20%.
3. With furniture waste, NO reduction increases with decreasing biomass particle size. With willow wood, NO reduction decreases slightly with decreasing particle size.
4. The kinetic model of basic reburning qualitatively agrees with experimental data for a wide range of initial conditions and thus correctly represents main features of the reburning process.

FUTURE ACTIVITIES

As discussed in *Introduction* section, this program is being conducted within joint Phase II USDA SBIR and DOE FETC projects. Future work on the Phase II SBIR project will include pilot scale combustion experiments on optimization of process parameters, as well as EPRI TAG economic analysis and engineering studies. Future work on the DOE FETC project will include experimental analysis of slagging and fouling in biomass reburning, as well as reburning vs. cofiring evaluation. Modeling activities will be continued and include kinetic modeling of biomass reburning, CFD modeling of reactive flows in combustion system, and subscale isothermal flow modeling of the boiler.

Total program is being conducted over a two-year period and will be concluded by October 1, 1999.

ACKNOWLEDGMENTS

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REFERENCES

- Bowman, C.T., Hanson, R.K., Gardiner, W.C. Jr., Lissianski, V., Frenklach, M., Goldenberg, M. and Smith, G.P. (1997) *GRI-Mech 2.11 - an Optimized Detailed Chemical Reaction Mechanism for Methane Combustion and NO Formation and Reburning*. GRI Report.
- Ho, L., Chen, S.L., Seeker, W.R. and Maly, P.M. (1993) *U.S. Patent 5,270,025*.
- Kau, C.J. and Tyson, T.J. (1987) A Computer Program for General Flame Analysis. *U.S. Environmental Protection Agency Report No. EPA-6000/7-87-027*.
- Miller, J.A. and Glarborg, P. (1996) in *Gas Phase Chemical Reaction Systems*. Springer series in Chemical Physics, V. 61 (Wolfrum, J., Volpp, H.-R., Rannacher, R. and Warnatz, J., Eds.), Springer-Verlag Berlin Heidelberg.
- Zamansky, V.M., Ho, L., Maly, P.M. and Seeker, W.R. (1996) *26 Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA.
- Zamansky, V.M., Maly P.M. and Ho, L. (1997) *ASME International Joint Power Generation Conference*, Denver, CO.